Constraining Dark Matter with Background Light

Sam McDermott

Thursday, Oct 17

FNAL

from 1309.4091,
with Rouven Essig, Eric Kuflik, Tomer Volansky, and Kathryn Zurek

plus work in progress with Ilias Cholis and Dan Hooper

Motivation

- Large swaths of well-motivated DM parameter space are currently up for grabs
- Photons (directly from decays or from FSR off charged particle final states) are generic DM decay products
- Data is "just sitting there" ready to use – what robust bounds on DM are available now?

Outline

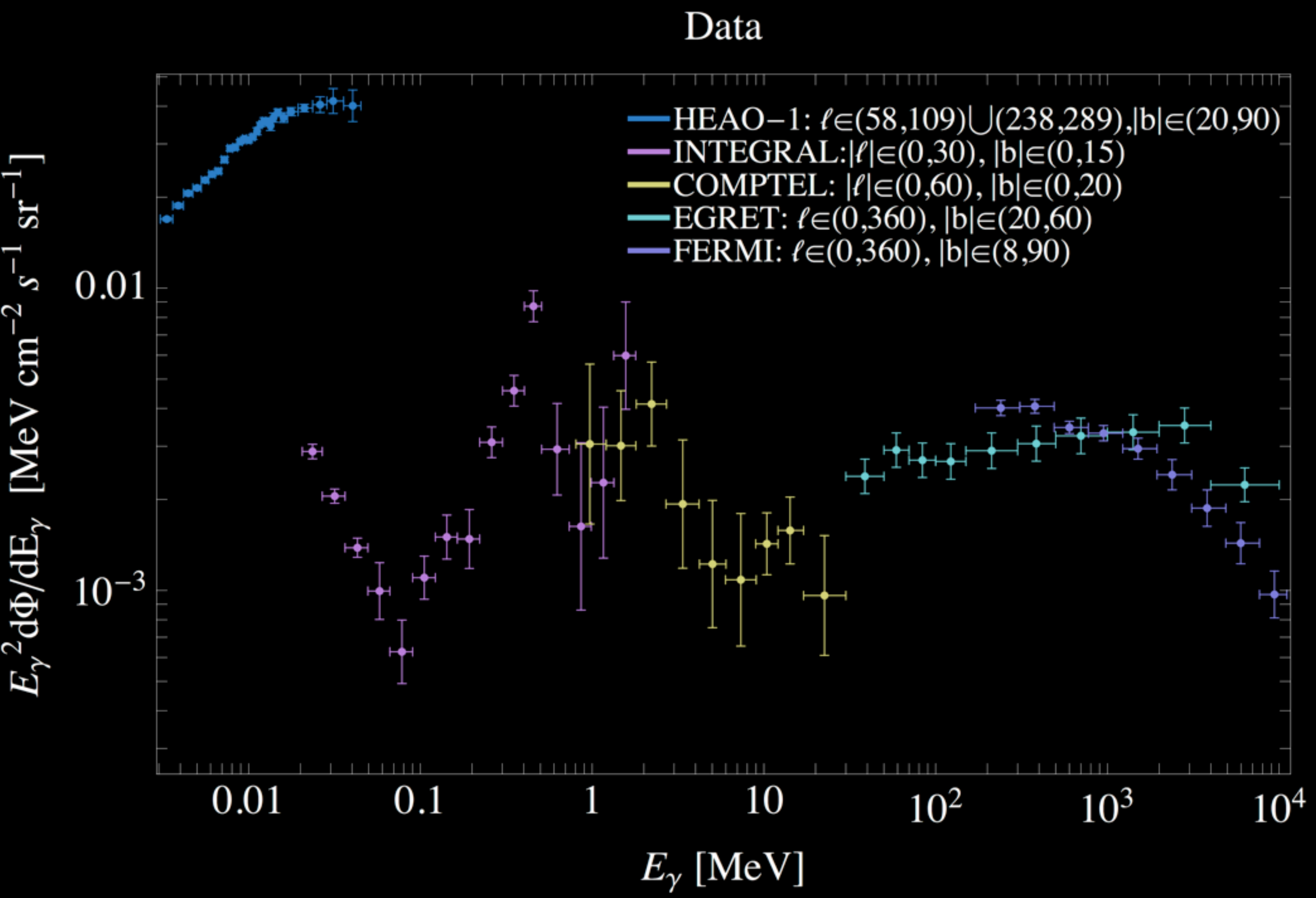
- Basics (what DM parameter space? what observations?)
- Models of light dark matter
- Statistical methodology
- Results
  - light decaying DM
  - more massive annihilating DM

"Light" Dark Matter

- our LDM is still cold – we are not interested in ALPs that form galactic scale BECs, etc.
- mass range: $\text{few keV} \lesssim m_{\mathrm{DM}} \lesssim \text{few GeV}$
- we assume standard cosmology (i.e., asymmetric or thermal production where appropriate)
- (emphasis on decaying dark matter)

“Diffuse” X-Rays and Gamma-Rays

- HEAO-1 (1977), INTEGRAL (2008), COMPTEL (1998), EGRET (2003), Fermi (2012) (21 months)
- Some observations near the galactic poles, some near the center
- *Not optimized for this kind of DM search*



Models We Can Constrain

- Hidden Photino – SUSY + hidden U(1). [The U(1) gets Higgsed and SUSY breaking is communicated through messengers; so we have massive hidden photon / photino with small mass splitting. The hidden photon kinetically mixes with the photon of U(1)EM, giving visible decays.]
- Sterile Neutrino – long-lived sterile neutrino. [FSR and radiative decays.]
- RPV Gravitino – sneutrino/photon mixing. [Planck-scale suppression gives a naturally small rate for gravitino decays. Fastest decay is gravitino > photon + neutrino.]
- Dipole Moment DM – generic higher-dimension operator. [Hidden Dirac particles with higher-dimension operator that couples them to the photon.]
- Dark scalar / pseudoscalar– generic decays. [FSR and direct decays.]

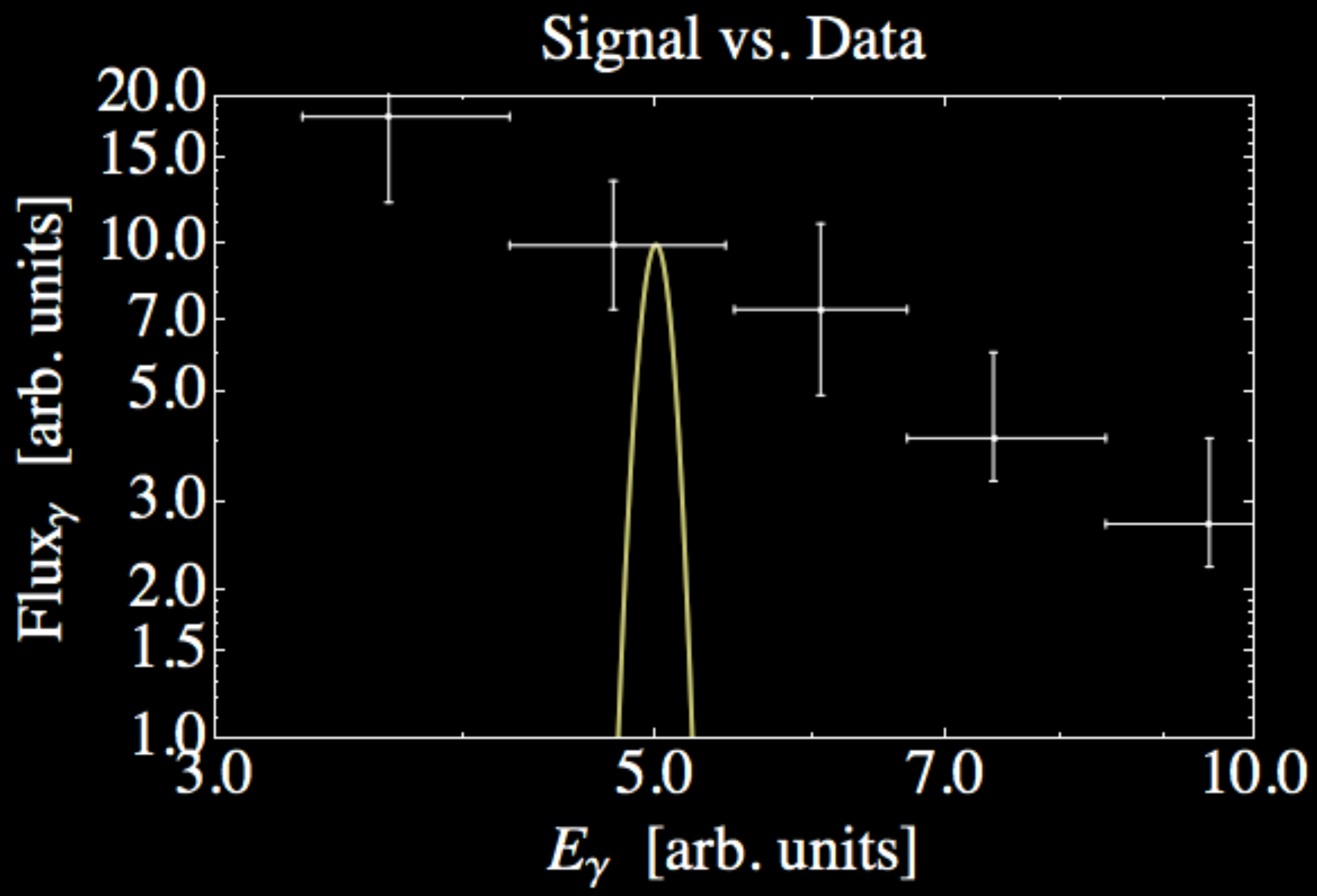
Analysis Method

- There are many different ways to carry out this kind of search:
  - spectral fit plus power law in sliding energy window (cf. Weniger)
  - precise background modeling (cf. Siegal-Gaskins; upcoming work)
  - "on-off" or template analyses (cf. Koushiappas + Geringer-Sameth; Finkbeiner + Slatyer; Hooper + Slatyer)
  - etc.
- Only direct photon production and primary FSR (light DM)
- We simply required (for every energy bin):

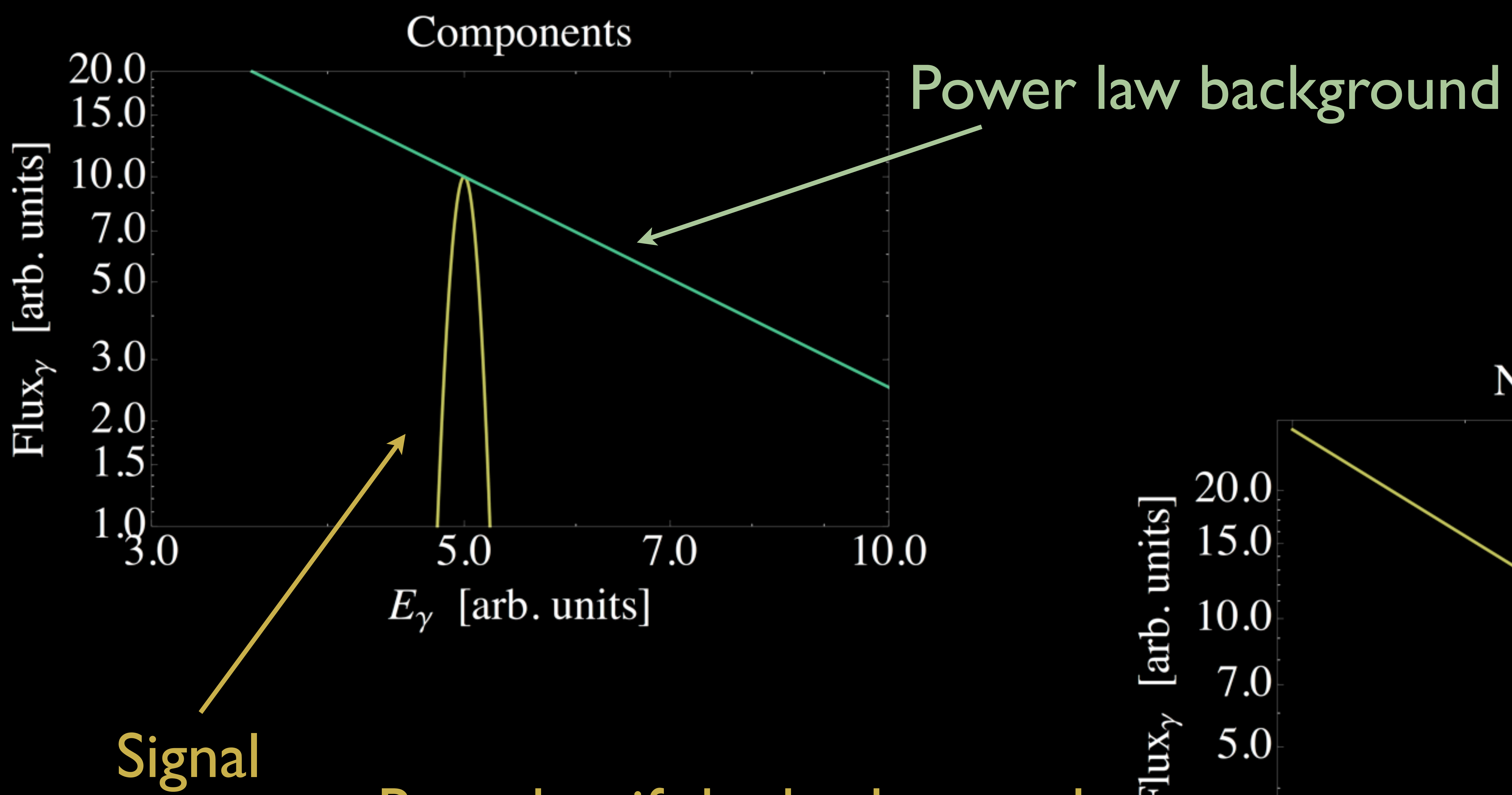
$$\mathrm{Flux}_{\mathrm{predicted}} \leq \mathrm{Flux}_{\mathrm{observed}} + 2 \times \mathrm{Error\ Bar}_{\mathrm{observed}}$$

- Robust results!

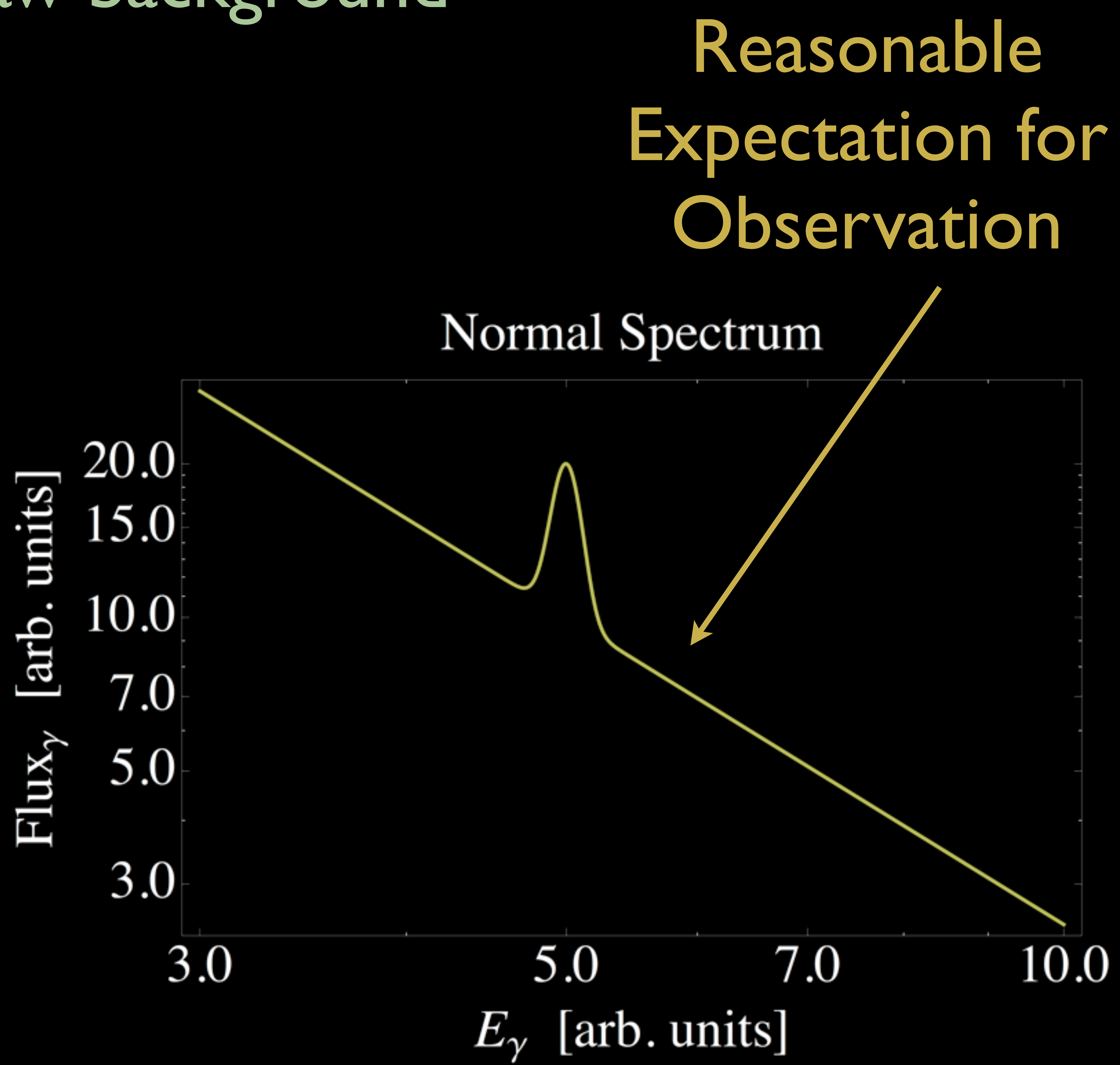
It looks like a slam dunk to rule out this signal



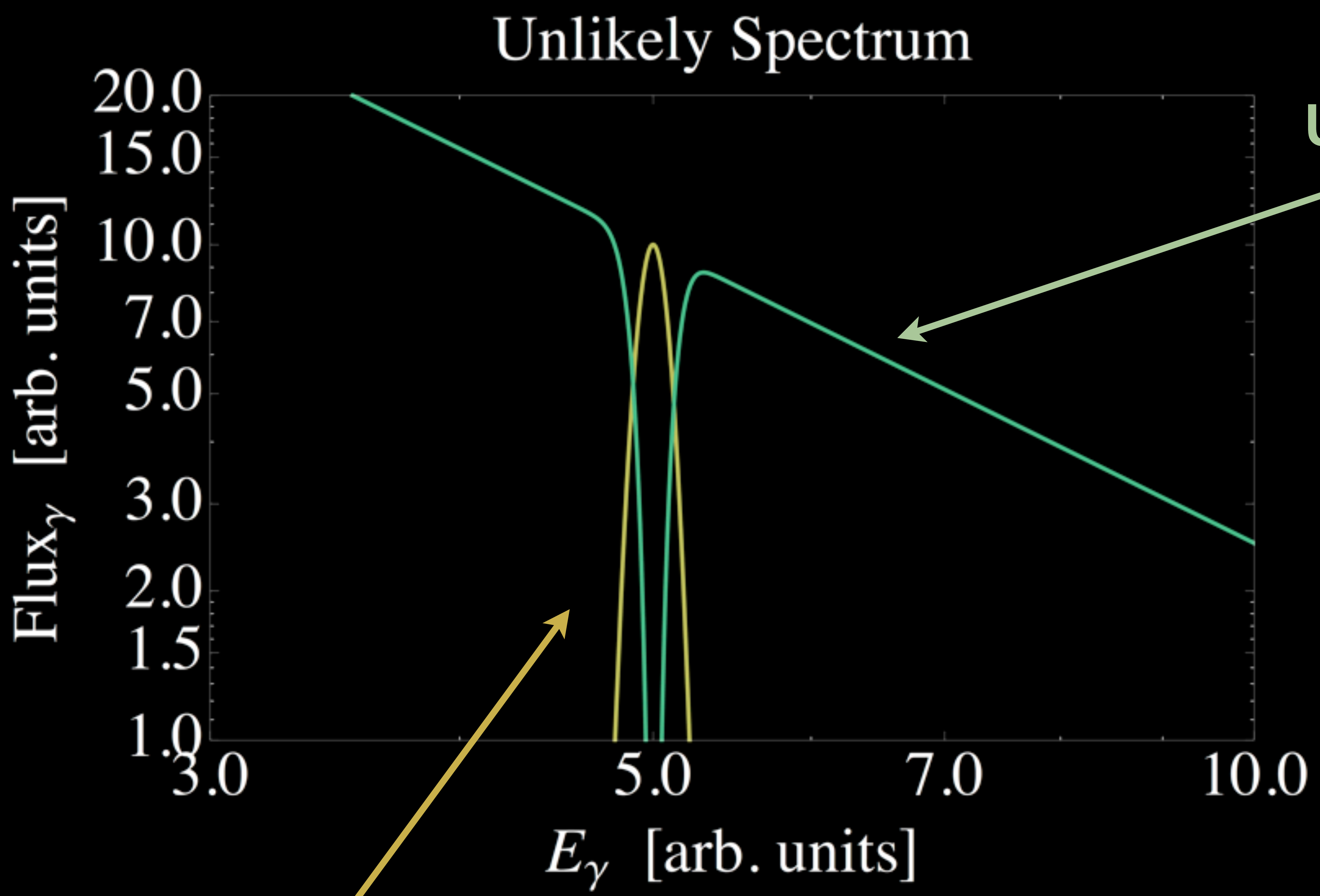
If we claimed to know the background power law, we could indeed rule it out



But what if the background does something crazy?



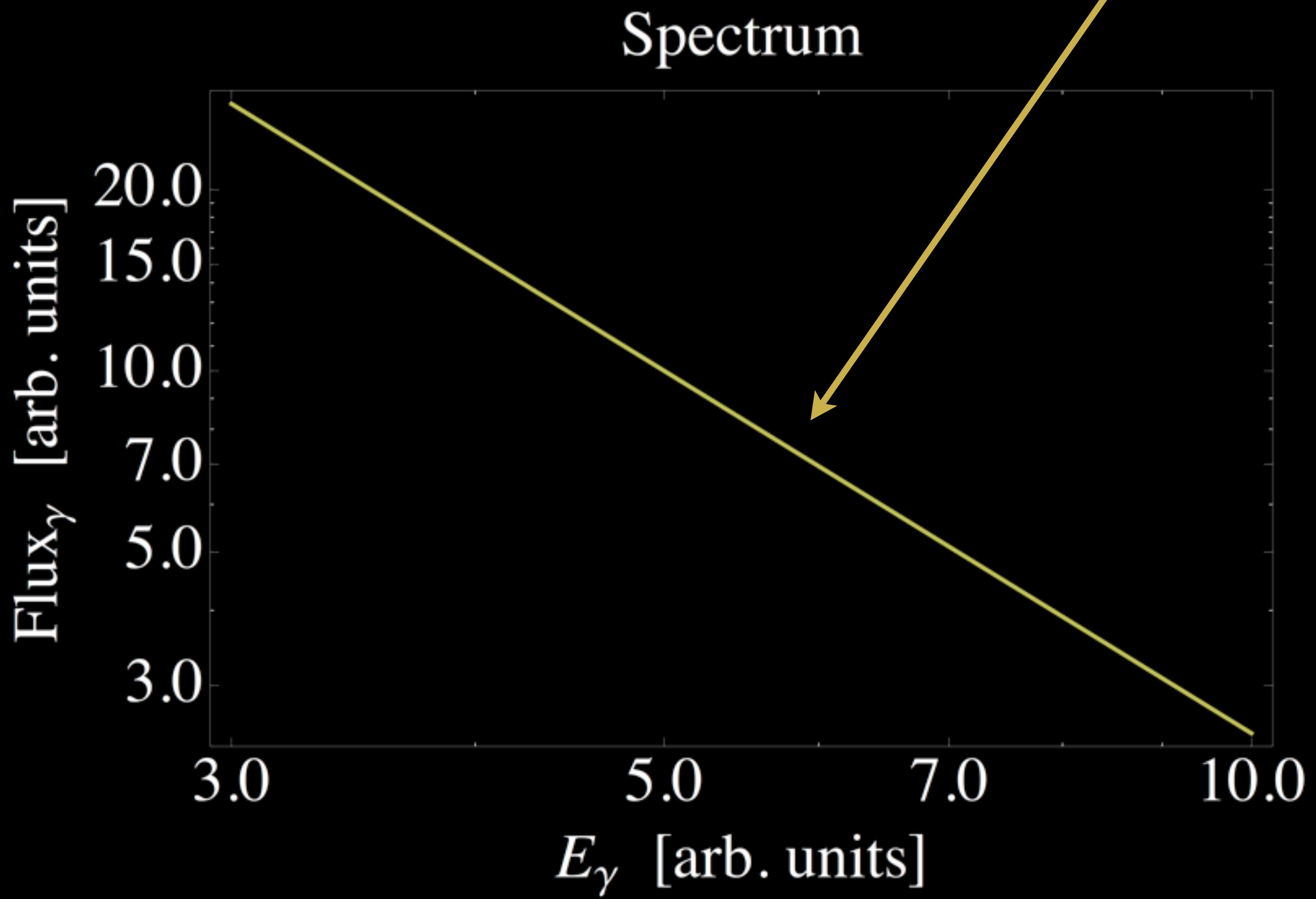
But what if the background does something crazy?



unlikely background

Signal

"Conspiracy" spectrum



(There is nothing crazy that the background can do to evade our bounds)

Theory Predictions

Galactic: $$\frac{d\Phi_{\gamma,\mathrm{G}}}{dE} = \frac{r_\odot}{4\pi}\frac{\rho_\odot}{m_{\mathrm{DM}}}\Gamma\frac{dN_\gamma}{dE}J(\Omega)$$

and extragalactic: $$\frac{d\Phi_{\gamma,EG}}{dE} = \frac{\Omega}{4\pi}\frac{\Gamma\Omega_{\mathrm{DM}}\rho_c}{m_{\mathrm{DM}}a_0 H_0}\int_0^\infty dz\,\frac{dN}{dE(z)}\frac{1}{\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}}$$

contributions.

Galactic dominates:

relative contributions set roughly by:

$$\rho_\odot r_\odot J(\Omega) \simeq \mathcal{O}(10^{-5}\ \mathrm{GeV}^3) \quad \text{vs.} \quad \rho_{\mathrm{DM}}/H_0 \simeq 5\times 10^{-6}\ \mathrm{GeV}^3$$

So the name of the game is...

Keep the astro/cosmology stuff as simple as possible

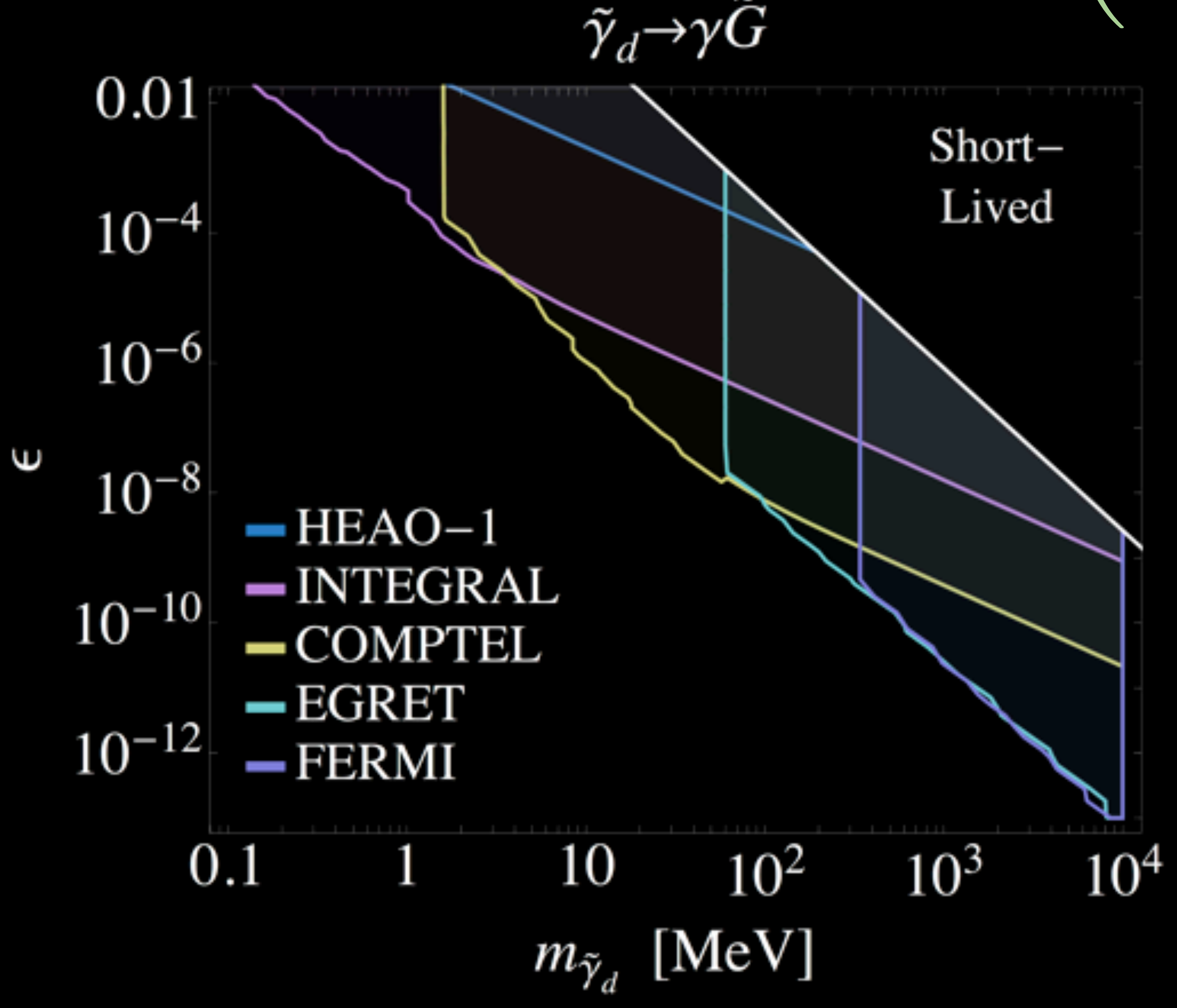
Particle physics enters through Γ and dN/dE_γ only:

dN/dE_γ is fixed by decay topology

Γ is fixed by the model

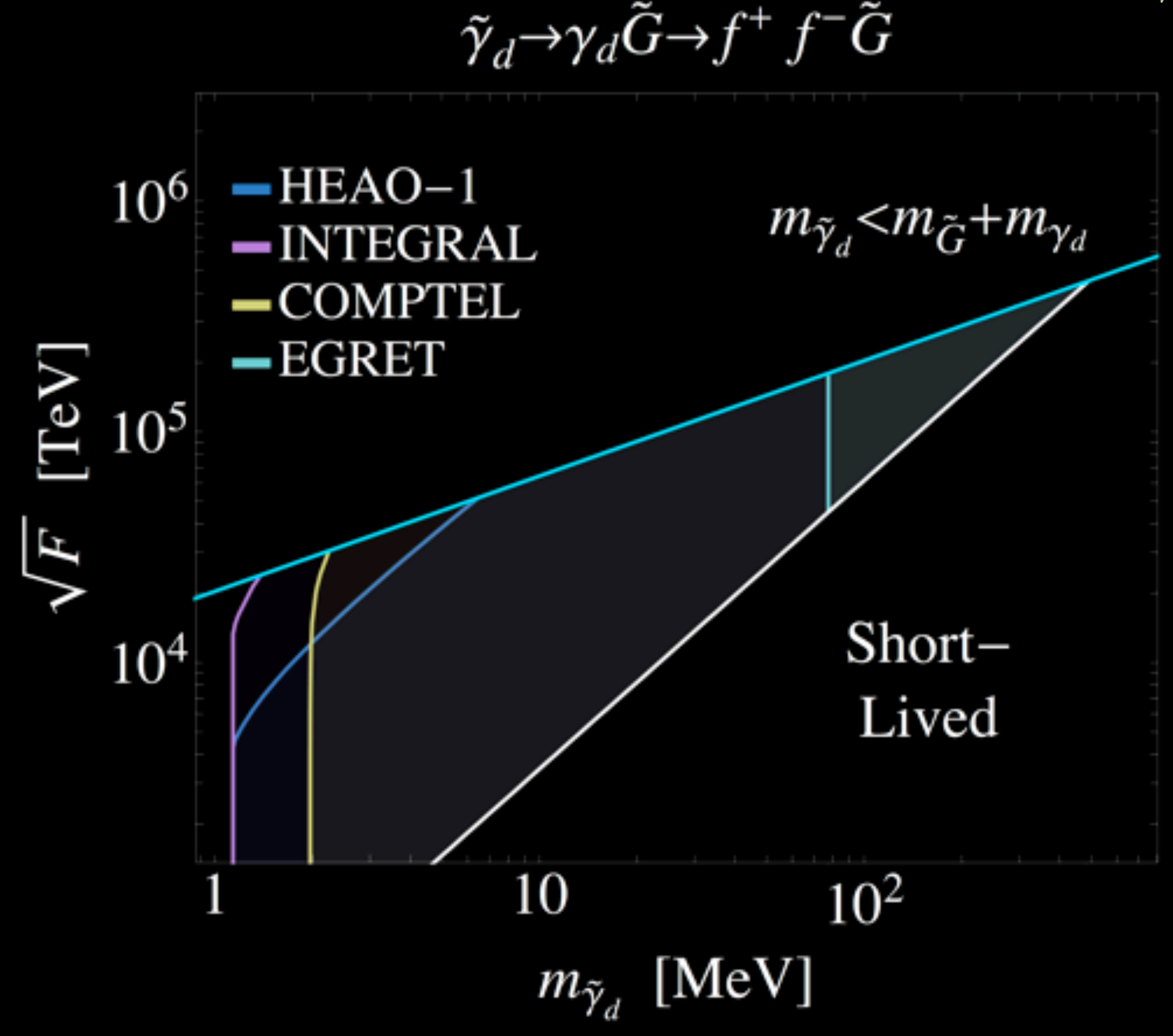
Dark Photino DM

$$\tau_{\tilde{\gamma}_d \to \gamma \tilde{G}} \simeq 3 \times 10^{23}\ \text{sec} \left(\frac{10^{-8}}{\epsilon}\right)^2 \left(\frac{10\ \text{MeV}}{m_{\tilde{\gamma}_d}}\right)^5 \left(\frac{\sqrt{F}}{100\ \text{TeV}}\right)^4$$



$$\sqrt{F} = 10^4\ \text{TeV}$$

$$\tau_{\tilde{\gamma}_d \to \gamma_d \tilde{G}} \simeq 3 \times 10^{20}\ \text{sec} \left(\frac{1\ \text{MeV}}{m_{\tilde{\gamma}_d}}\right)^5 \left(\frac{\sqrt{F}}{10^4\ \text{TeV}}\right)^4 \left(1 - \frac{m^2_{\gamma_d}}{m^2_{\text{DM}}}\right)^{-4}$$



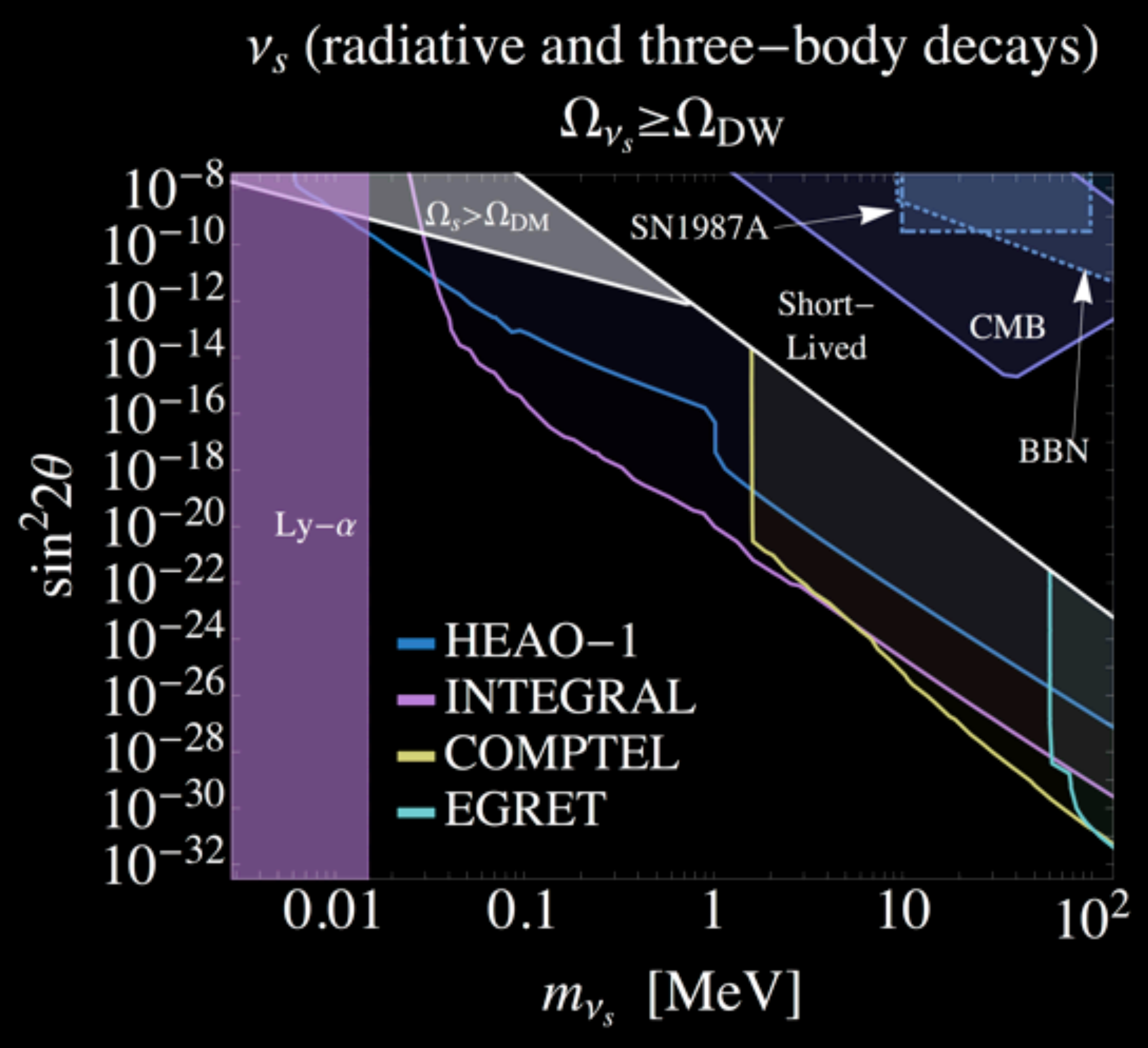
$$m_{3/2} = \frac{F}{\sqrt{\frac{3}{8\pi}} M_{\text{Planck}}}$$

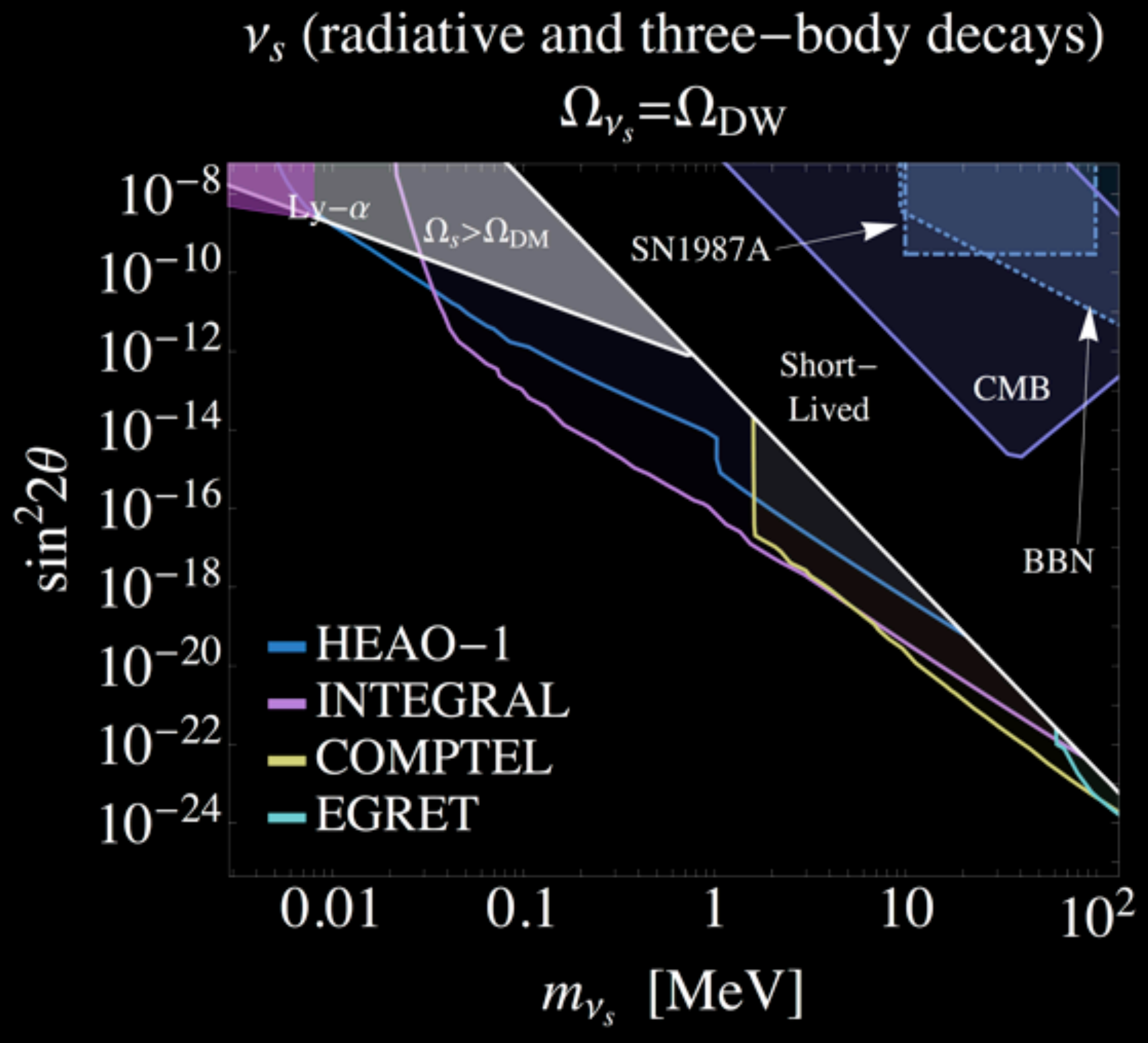
Sterile Neutrino DM

$$\tau_{\nu_s \to \nu\gamma} \simeq 1.8 \times 10^{17} \text{ sec} \left(\frac{10 \text{ MeV}}{m_\chi}\right)^5 \left(\frac{\sin\theta}{10^{-8}}\right)^{-2}$$

$$\tau_{\nu_s \to \nu_\alpha e^+ e^-} \simeq 2.4 \times 10^{15} \text{ sec} \left(\frac{10 \text{ MeV}}{m_\chi}\right)^5 \left(\frac{\sin\theta}{10^{-8}}\right)^{-2}$$

Three-body and radiative decays contribute to photon background at similar levels

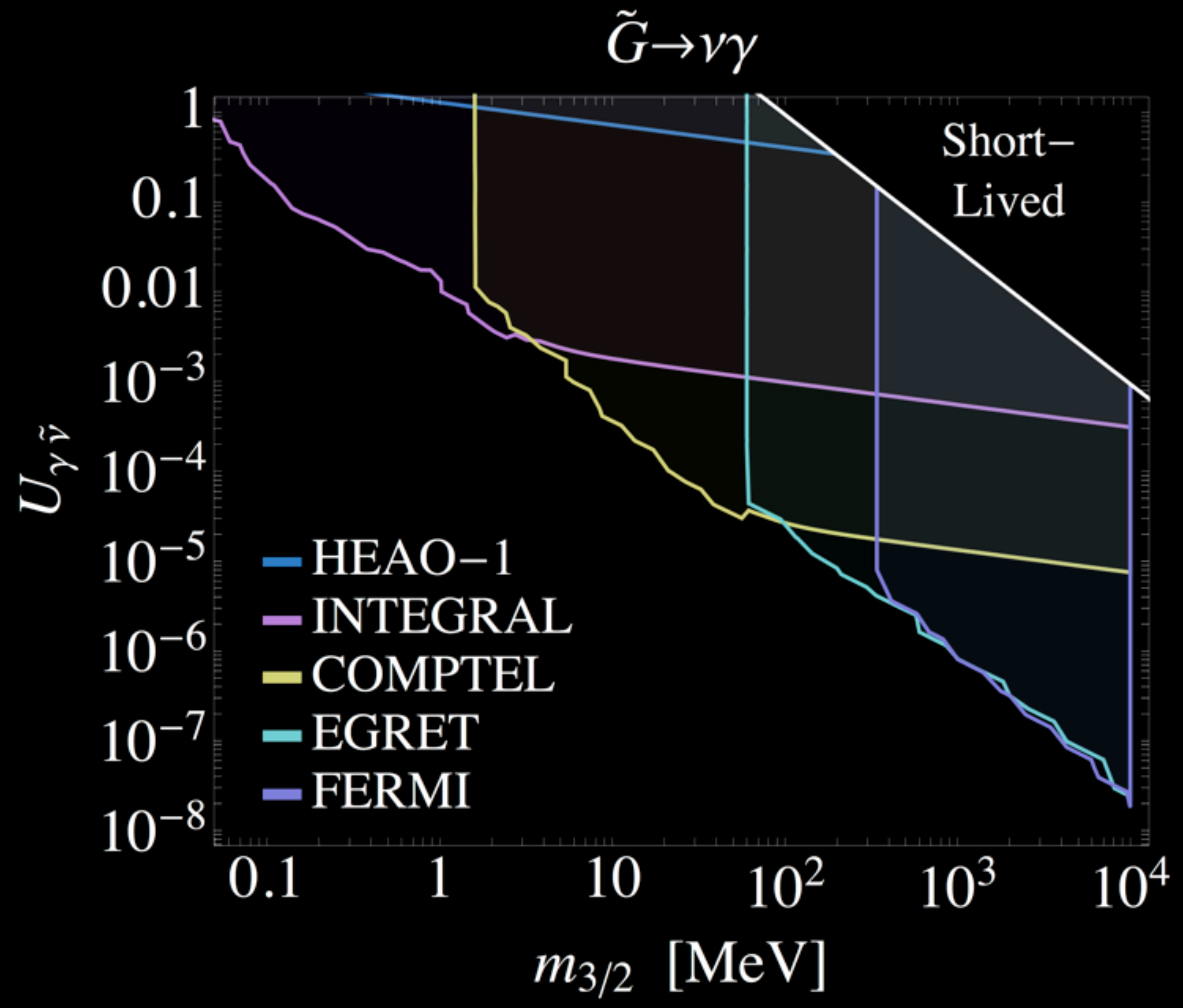




Gravitino DM in an RPV vacuum

$$\tau_{\widetilde{G}\to\nu\gamma} \simeq 3.8\times 10^{28}\ \mathrm{sec}\left(\frac{10\ \mathrm{MeV}}{m_{3/2}}\right)^3\left(\frac{10^{-4}}{U_{\gamma\widetilde{\nu}}}\right)^2$$

line-like decay dominates three-body decay

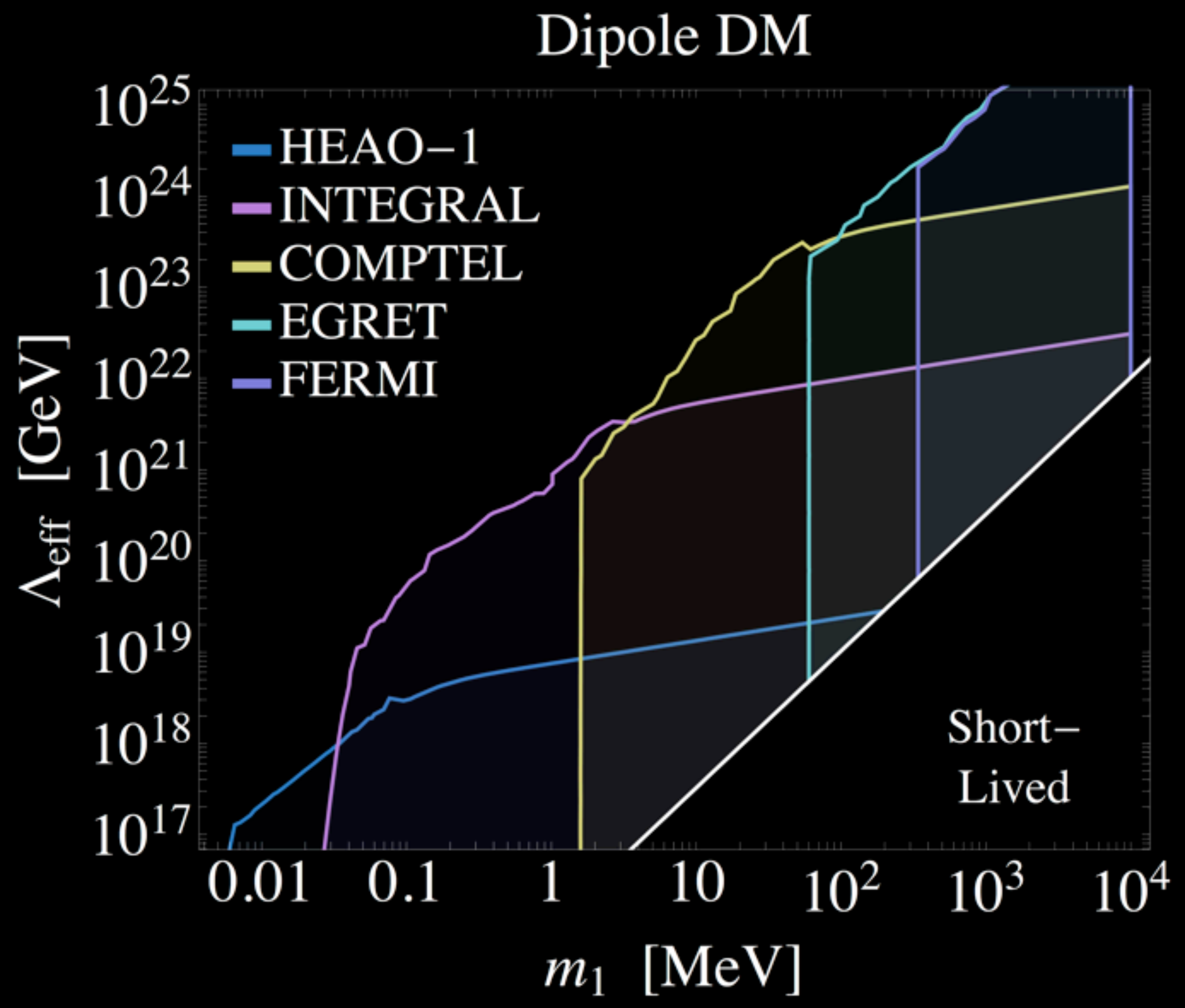


Dipole DM

$$\mathcal{L} \supset \frac{\lambda}{\Lambda} \bar{\chi}_2 \sigma^{\mu\nu} \chi_1 F_{\mu\nu}$$

$$\tau_{\rm dipole} \simeq 4.1 \times 10^{20}\ {\rm sec} \left(\frac{10\ {\rm MeV}}{m_1}\right)^3 \left(\frac{\Lambda_{\rm eff}}{10^{19}\ {\rm GeV}}\right)^2$$

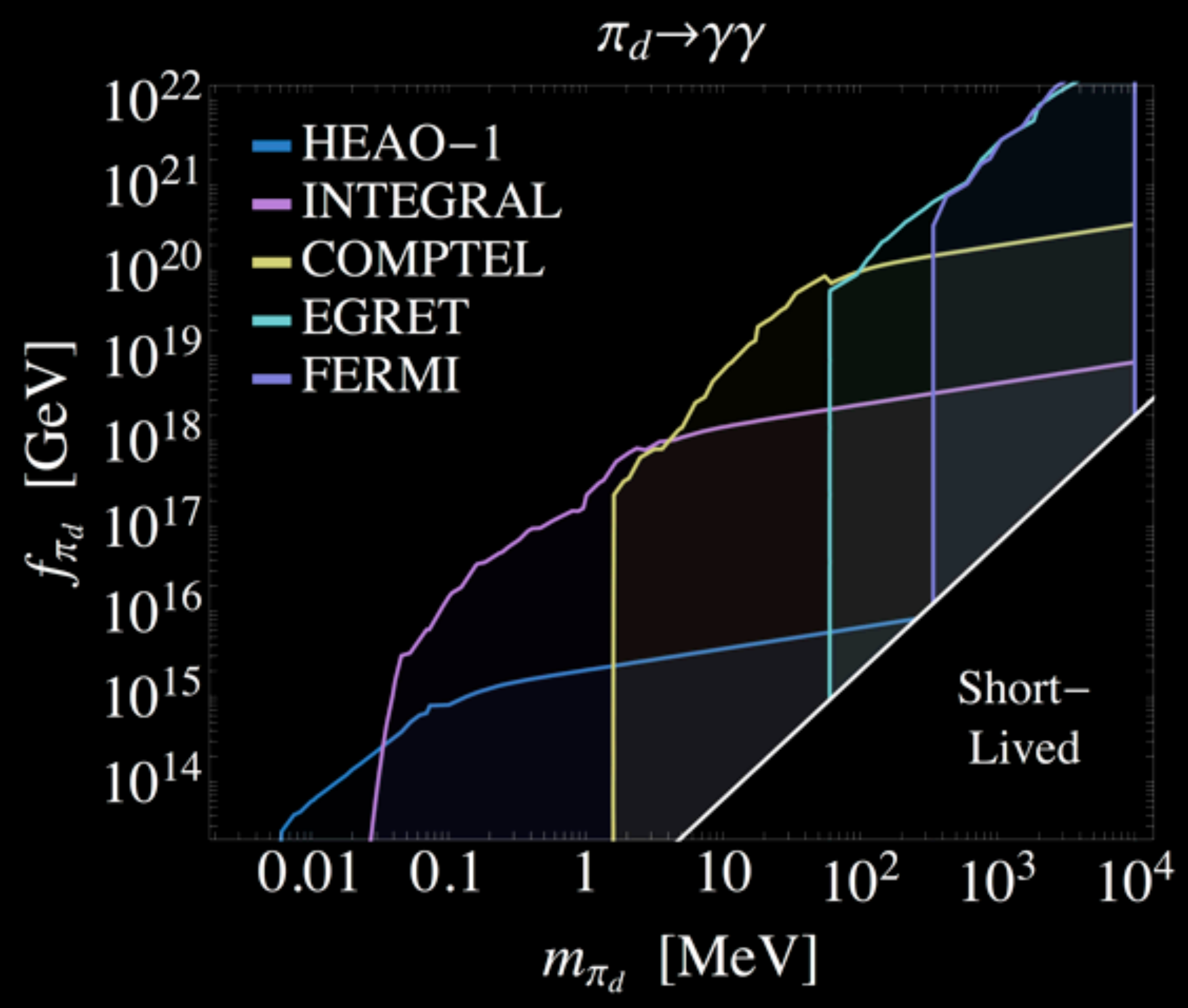
dimension 5 operator
can be strongly constrained

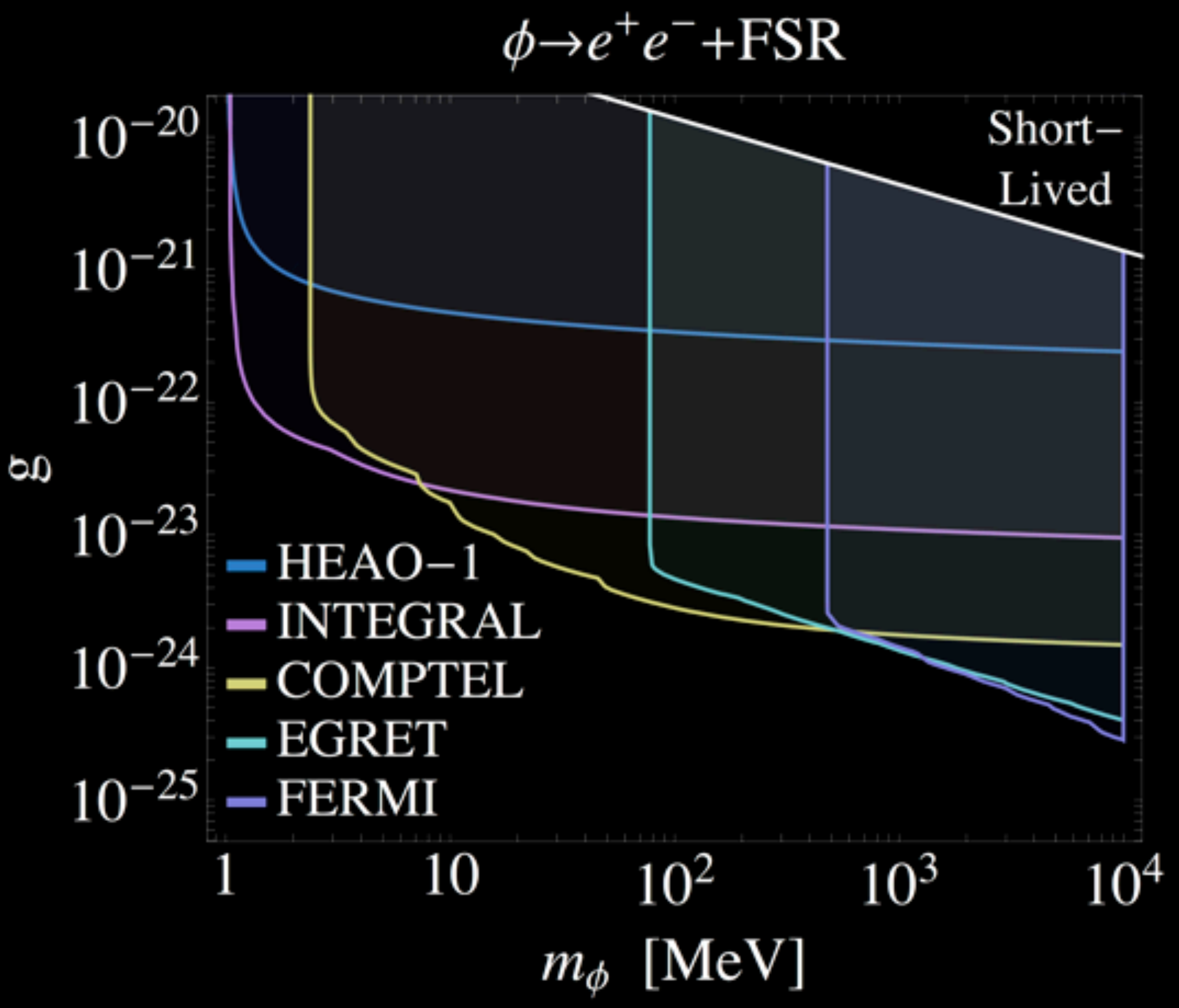


$(\Lambda_{\rm eff} \equiv \Lambda/\lambda)$

Dark (pseudo)scalars

$$\tau_{\pi_d \to \gamma\gamma} \simeq 1.1 \times 10^{20}\ \mathrm{sec} \left(\frac{10\ \mathrm{MeV}}{m_{\pi_d}}\right)^3 \left(\frac{f_{\pi_d}}{10^{15}\ \mathrm{GeV}}\right)^2$$



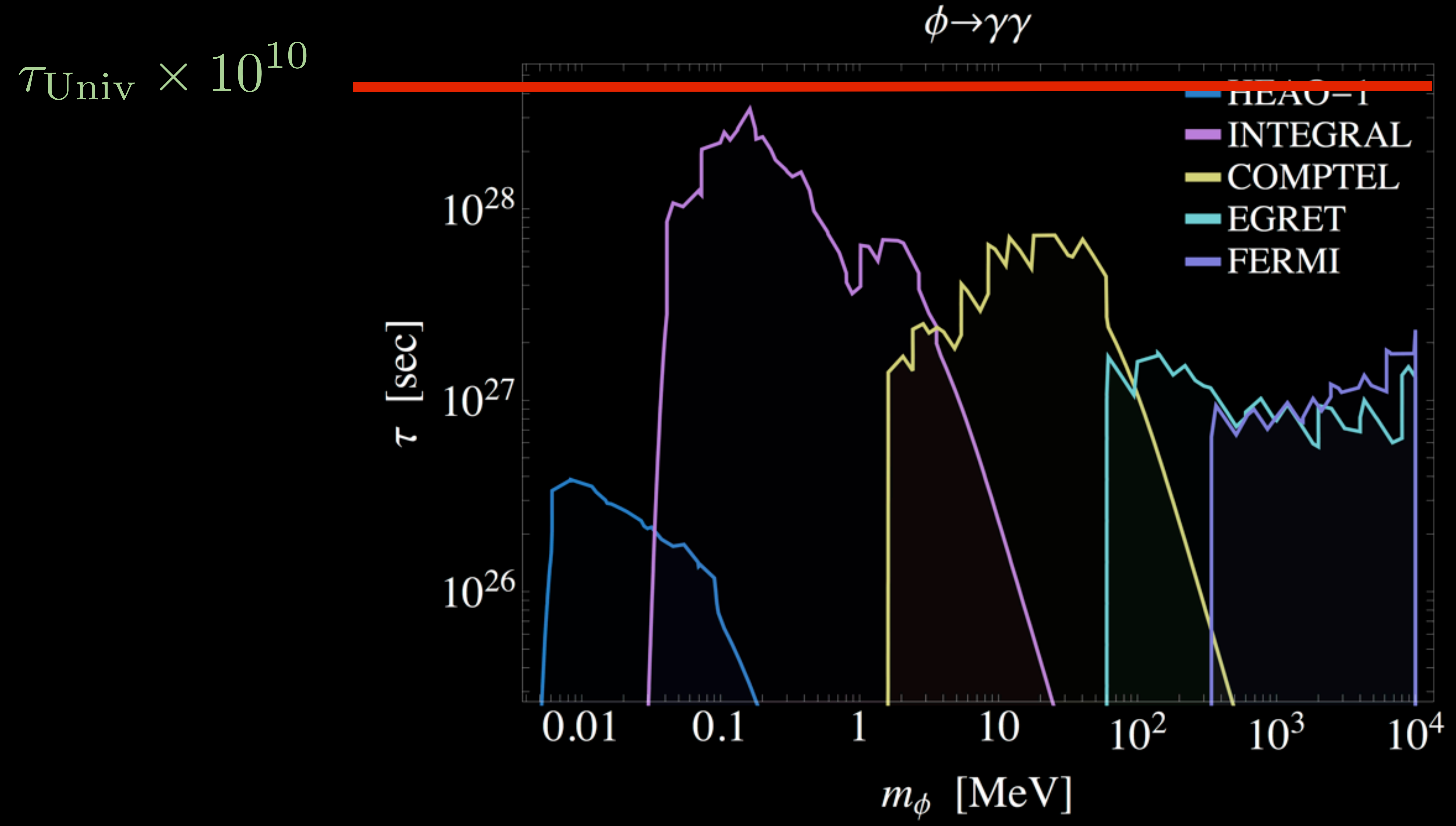


$$\tau_{\phi \to e^+e^-} \simeq 8.3 \times 10^{18}\ \mathrm{sec} \frac{10\ \mathrm{MeV}}{m_\phi} \left(\frac{10^{-20}}{g_a}\right)^2$$

Halftime

- Those were the model-dependent bounds
  - bounds on model-specific parameters (mixing angles, decay constants, etc.)
  - very strong for dimension<6, non-Planck-suppressed operators
- About to show model-independent bounds
  - just the lifetime – mass plane from now on
  - lifetime bounds from 6 (FSR photons) to 10 (direct photons) orders of magnitude stronger than 1/H0

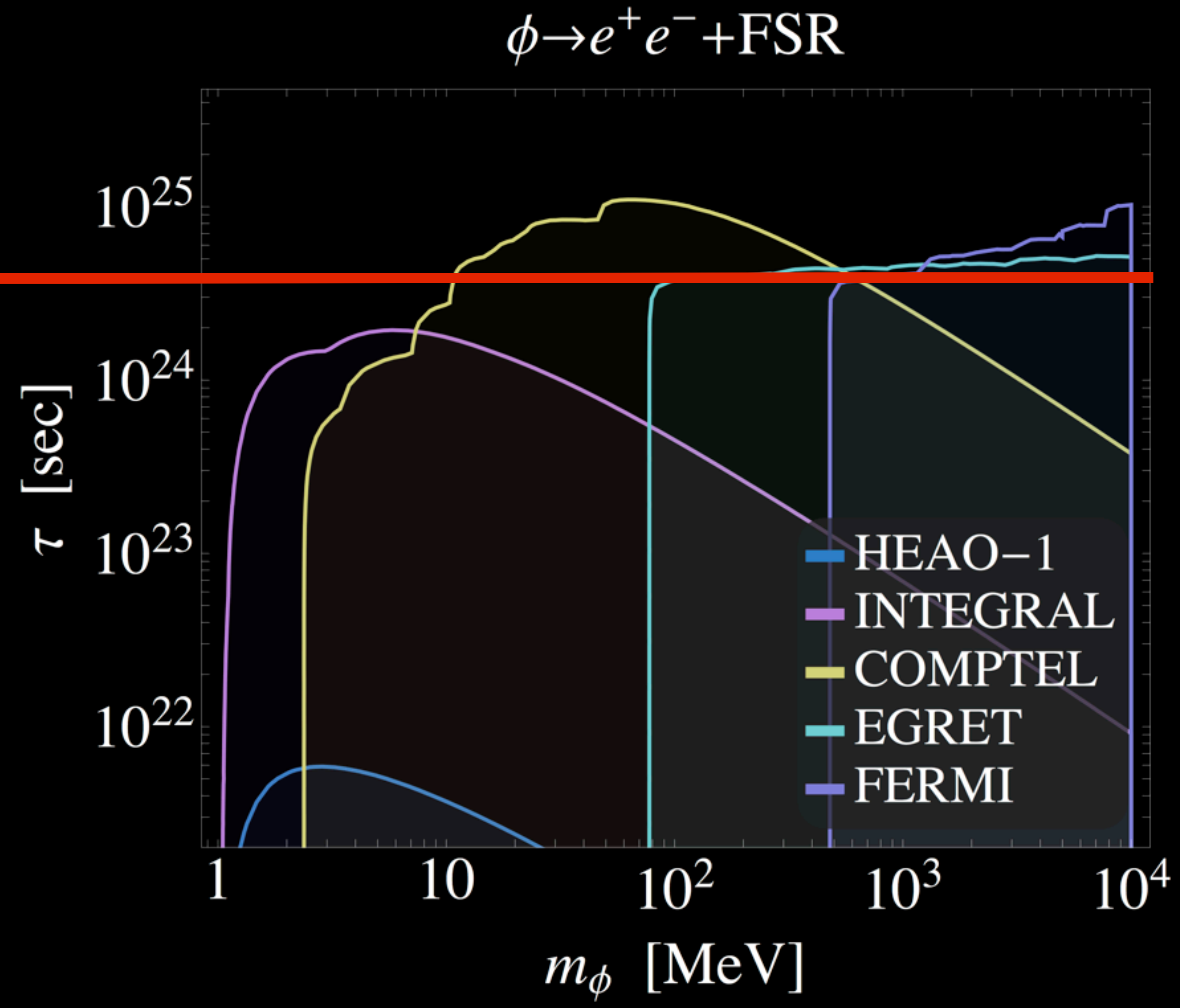
Photon Line



$\phi \to \gamma\gamma$
$\tau_{\mathrm{Univ}} \times 10^{10}$
HEAO−1
INTEGRAL
COMPTEL
EGRET
FERMI
10^{28}
10^{27}
10^{26}
τ [sec]
0.01
0.1
1
10
10^2
10^3
10^4
m_ϕ [MeV]

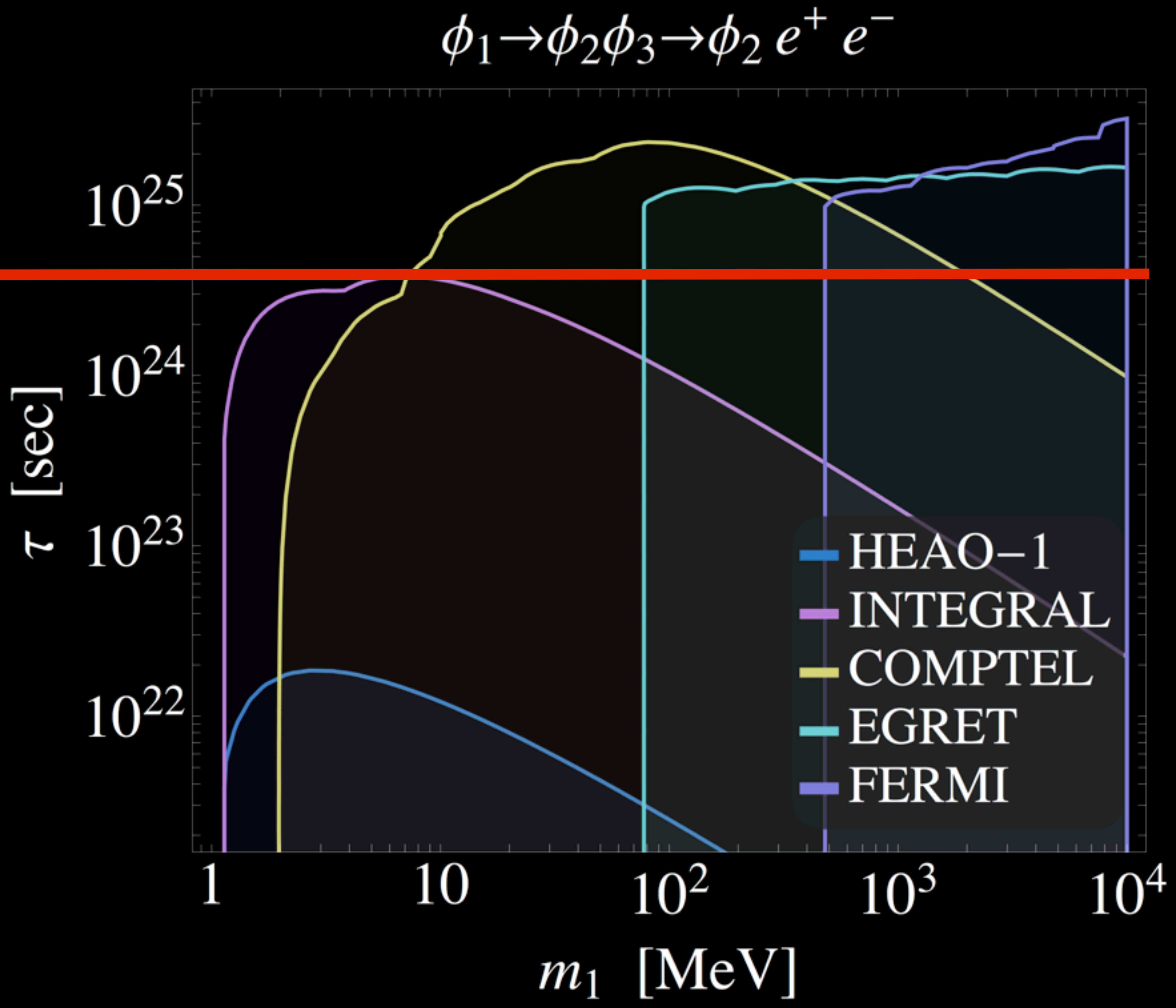
e+ e- (FSR)

$\tau_{\rm Univ} \times 10^6$

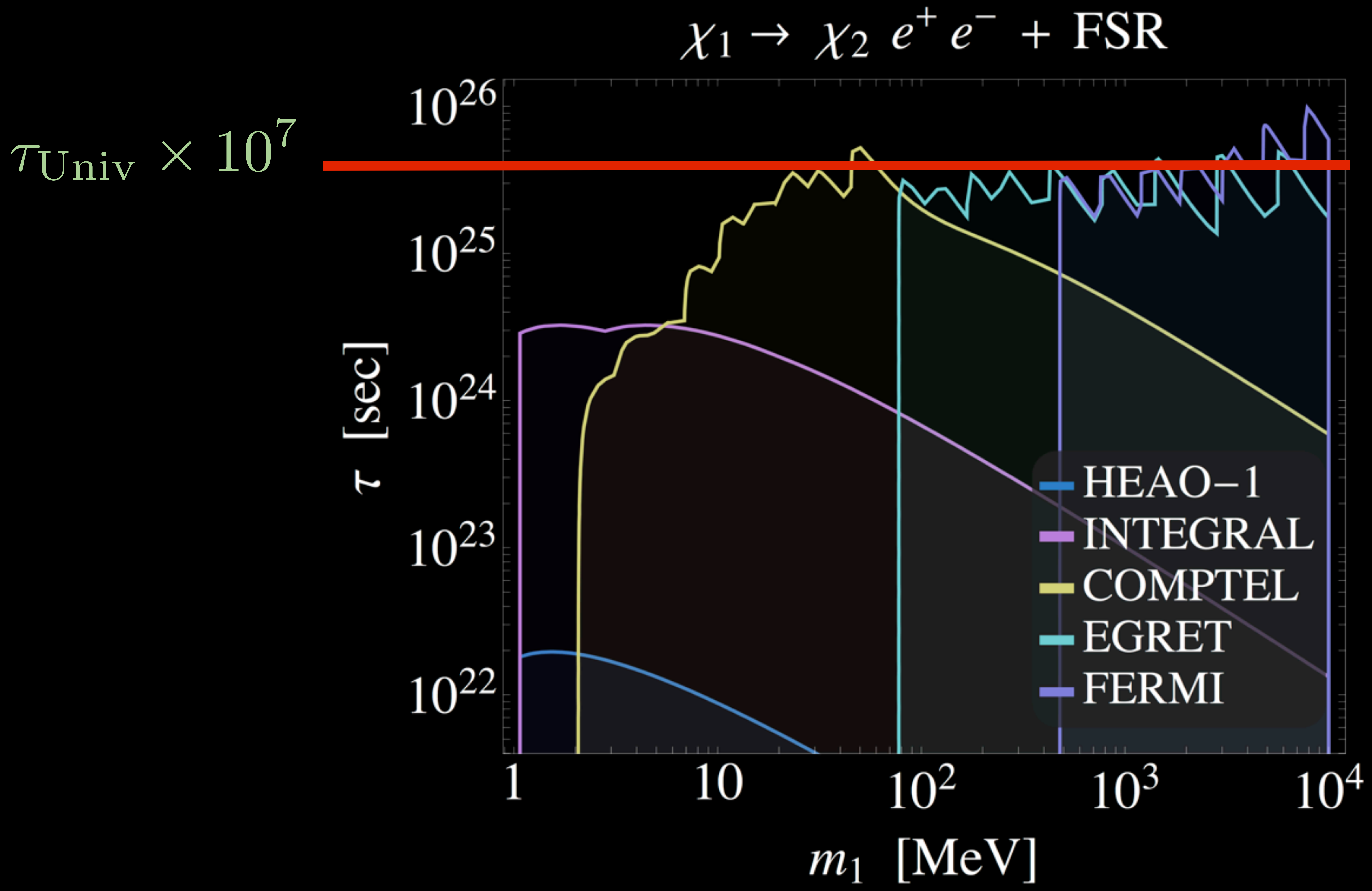


e+ e- (FSR), boosted

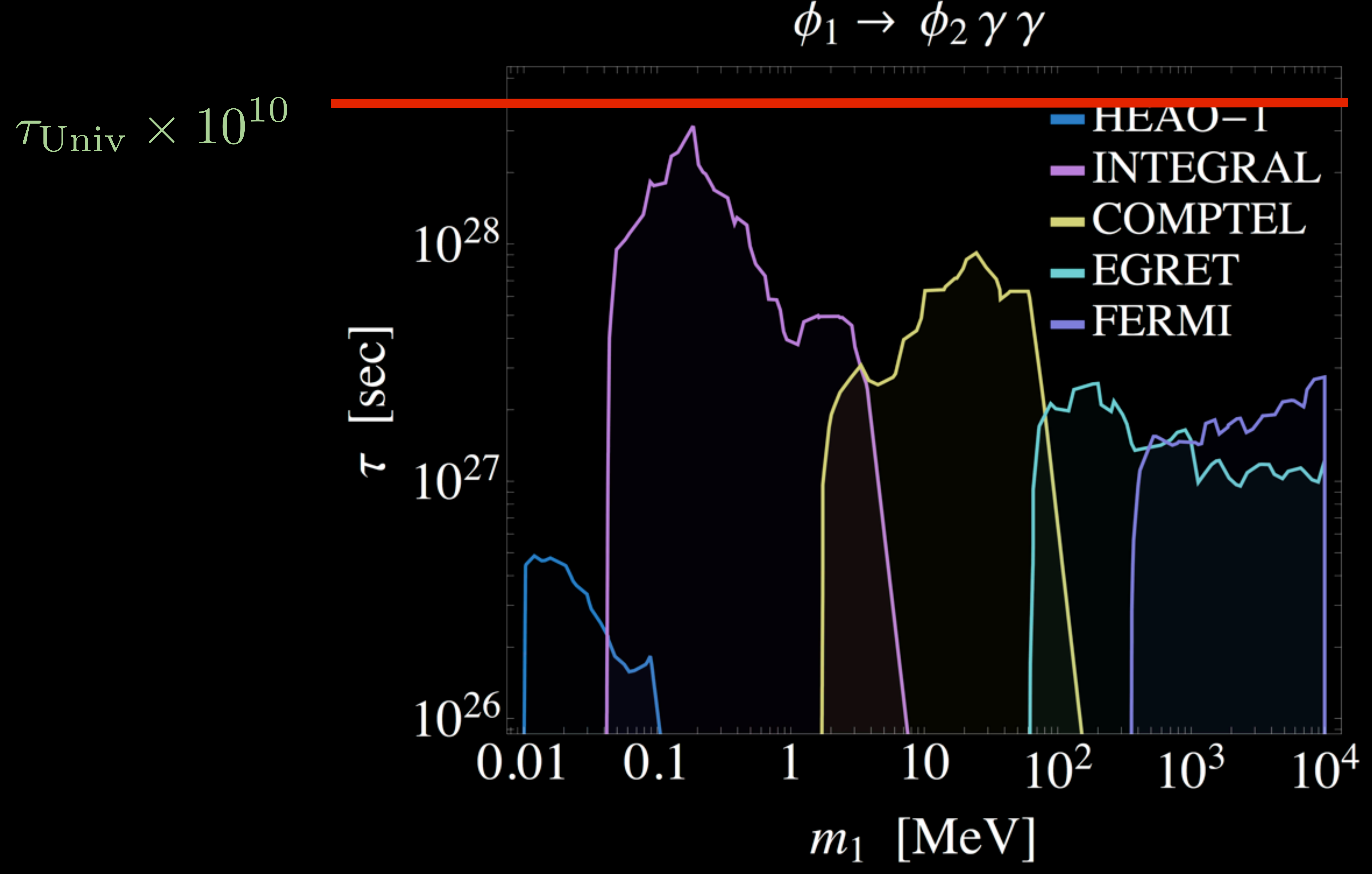
$\tau_{\mathrm{Univ}} \times 10^6$



e+ e- (FSR), three-body

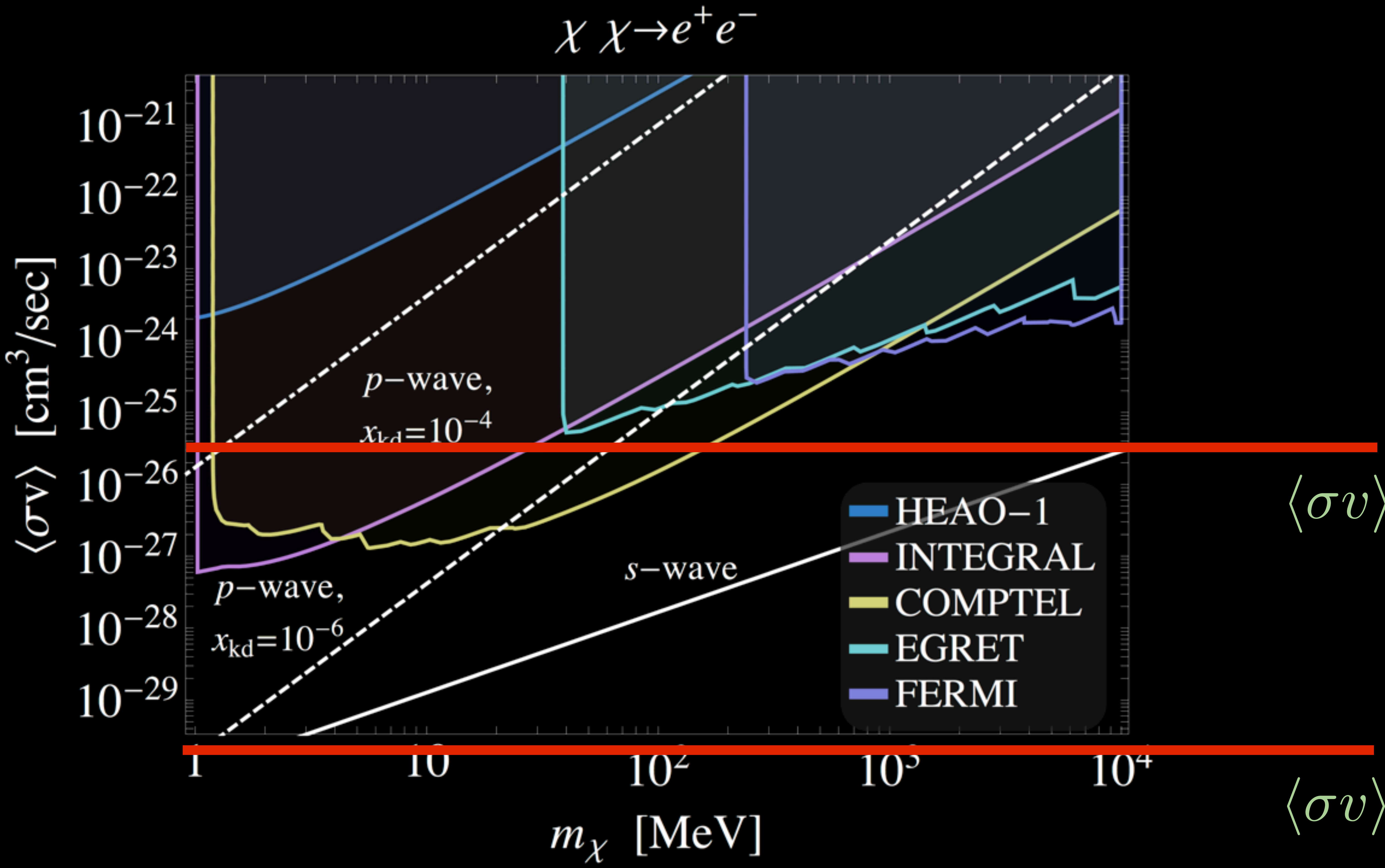


three-body, directly to photons



e+ e- (FSR), annihilating*

*smooth galactic component only



$\langle\sigma v\rangle_{\mathrm{th},s\,\mathrm{wave}}$

$\langle\sigma v\rangle_{\mathrm{th},p\,\mathrm{wave}}$

Rough guess: extragalactic vs. galactic

(Very) naïvely, the smooth galactic part dominates...

$$\rho_\odot^2 r_\odot J_A(\Omega) \simeq \mathcal{O}(10^{-46}\ \mathrm{GeV}^7) \quad \text{vs.} \quad \rho_{\mathrm{DM}}^2 \Omega / H_0 \simeq \mathcal{O}(10^{-51}\ \mathrm{GeV}^7)$$

(solid angle for outer galaxy)

(caveats)

...but canonical (Press-Schechter) overdensity increases rho by ~O(200)

Substructure increases it even more (peaks within peaks)

DM Annihilation

- The smooth galactic component is actually subdominant compared to annihilation in subclusters
  - extragalactic subclusters (at all redshifts)
  - galactic “satellites” (subhalos and sub-subhalos and sub-sub-sub...)
- However, the substructure contribution is model dependent
  - halo mass function
  - satellite mass function
  - optical depth, etc

Extragalactic Annihilations

$$I(E) = \int dz \frac{d\chi}{dz} W\left[E \cdot (1+z), \chi\right] \langle \delta^2 \rangle$$

Intensity –
how many photons we'd
see in a given experiment;
units 1/(cm^2 GeV sec sr)

"Window function" –
which photons can get to us

"Density multiplier" –
how many places the
photons can come from

Photons come from all redshifts,
and are dominantly from high-density regions

Extragalactic Annihilations, cont.

$$W(E,z) = \frac{\langle \sigma v \rangle}{8\pi} \left(\frac{\Omega_{\rm DM} \rho_c}{m_{\rm DM}} \right)^2 (1+z)^3 \frac{dN_\gamma}{dE} \exp\left[-\tau(E,z)\right]$$

photon spectrum per annihilation

“optical depth” – odds that a photon of energy E from redshift z scatters off CMB

“halo mass function” – number density of halos of mass M per unit redshift

“subhalo boost factor” – additional boost factor for substructure

$$\langle \delta^2 \rangle = \left(\frac{1}{\Omega_{\rm DM} \rho_c} \right)^2 \int dM \frac{dn(M,z)}{dM} \left[1 + b_{\rm sh}(M)\right] \int dV \rho^2_{\rm host}(r, M)$$

Lots of ingredients...

- dN/dE from PPPC DM ID (Pythia+EW corrections)
- optical depth from semi-analytic modeling (Gilmore, Primack, et al)
- halo mass function and subhalo boost factor from semi-analytic fits to simulations

Plenty of backgrounds

- star forming galaxies
- unresolved blazars / misaligned AGN
  - radio galaxies (BL Lactaea objects, FSRQs, etc.)
- millisecond pulsars (...)

(...still in progress)

- Still in progress, but moving rapidly
- Expectation is to bound annihilation below the thermal cross-section for DM mass up to ~O(10 GeV)
- Similar to observations from dwarfs (Fermi stacked dwarf spheroidals), line searches (Weniger; Tempel et al; Finkbeiner et al; Fermi), and bounds from power spectrum (Ando and Komatsu)
- Powerful complementary probe

Conclusions

- Bounds on light decaying DM from the galactic diffuse background are strong even though observations are not DM-centric
- Looking outside the galaxy makes it possible to put similar constraints on more massive annihilating DM